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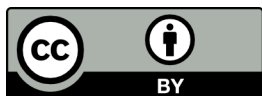
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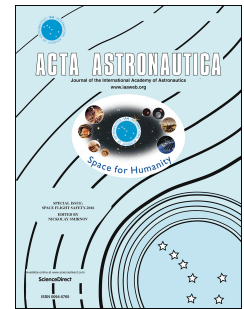
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Title:

ISRU technology deployment at a lunar outpost in 2040: a Delphi survey

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Abstract

The purpose of this study was to deploy a Delphi expert elicitation methodology to better understand the technical and policy challenges facing the development of a sustainable lunar outpost in 2040, including the types and scale of ISRU deployment. We used a three-round Delphi survey with an open first round and specific questions in later rounds using a four-point Likert scale and two ranking exercises to assess energy technologies and inhibiting factors. In order to provide more certainty to our potential participants regarding their input, and boost engagement, the study deployed a three-round approach that was communicated to our potential participants and decided ex-ante. Potential participants were identified from the literature and academic networks as those who had made significant contributions to the fields of; ISRU technologies, space architecture, space-qualified power systems, and space exploration. The study identified around 20 major themes of interest for researchers in the first round and asked participants to rate their agreement with a number of statements about a hypothetical lunar outpost in 2040. From the group responses, we identified three major technical challenges for the development of a lunar outpost in 2040; developing high power energy infrastructure, lander and vehicle ascent capacity, and mission architectures and technical approaches. We also identified three major policy challenges for the development of a lunar outpost in 2040; US and global political instability, possibility of an extended timeframe for the first lunar landing, and political distaste for nuclear energy in space. The group was uncertain about the precise energy mix at the outpost as a result of uncertainty regarding electrical loads, but there was general agreement that solar PV would be a significant contributor. Whether nuclear power sources might play a useful role proved to be very uncertain, with some participants noting a political distaste for space nuclear power systems. However, the proposition gained two votes in each ranking position, suggesting it has a flat distribution including both supporters and detractors.

Keywords

Space exploration, Space policy, Space power systems, ISRU, Lunar construction, Lunar habitat

aspect of the future, but to illuminate the areas that are relatively well bounded and those that are very uncertain.

The general criterion for stopping the iterations is group consensus on all questions. If between rounds, the researchers determine that a question has reached consensus, it is typically no longer submitted in the subsequent rounds, and this process is repeated until there are no questions left, or the researcher believes that consensus will not be reached as the results remain stable between rounds [25–29]. However, within the literature, there are diverse definitions of consensus, using numerous descriptive statistics that seem to be applied arbitrarily in most cases [26,29,36]. A more useful criterion for stopping the survey iterations is the stability of the answers between rounds [26].

2. Methodology

We used a three-round Delphi survey with an open first round and specific questions in later rounds using a four-point Likert scale. In order to provide more certainty to our potential participants regarding their input, and boost engagement, the study deployed a three-round approach that was communicated to our potential participants prior to participation, and decided ex-ante.

2.1. Participant selection

Potential participants were identified from the literature and academic networks as those who had made significant contributions to the fields of; ISRU technologies, space architecture, space-qualified power systems, or space exploration. Some were executives or academics while others were researchers at NASA or ESA, but all were relevant subject matter experts. Once identified, the participants were approached via email. The study aimed to recruit a minimum of 12 participants to ensure that at normal dropout rates, 10 of those 12 participants would complete the study. This ensured we were within the appropriate sample size parameters of Delphi studies [29,31–34]. 28 subject matter experts were invited to participate, of whom 12 accepted and were progressed to the first round of the study, where 2 participants dropped out, leaving us within the required sample size parameters for analysing the results.

2.2. The expert pool

The pool was made up of roughly half academia, and half space agency or space industry researchers and executives. Therefore, the use of the h-index does not fully encapsulate the experience and knowledge of the pool as many of the participants focus was on project work rather than academic publishing. The mean h-index was 8.2. Taking only the academics, the mean h-index is 13.25.

To better represent the calibre of the whole group, industrial and academic, we assessed each participants years active in industry or academia, named here as ‘experience’. The mean experience in years of the whole group was 16.8, determined in our preliminary participant research and evaluation, where we identified each participant’s career starting year. The total years of experience of our pool was 168.

Figure 1 shows the distribution of experience across five-year ‘bins’, demonstrating the breadth of experience of the whole group whilst protecting the anonymity of the participants. This encapsulates the experience of the industrial participants in a way that h-index does not.

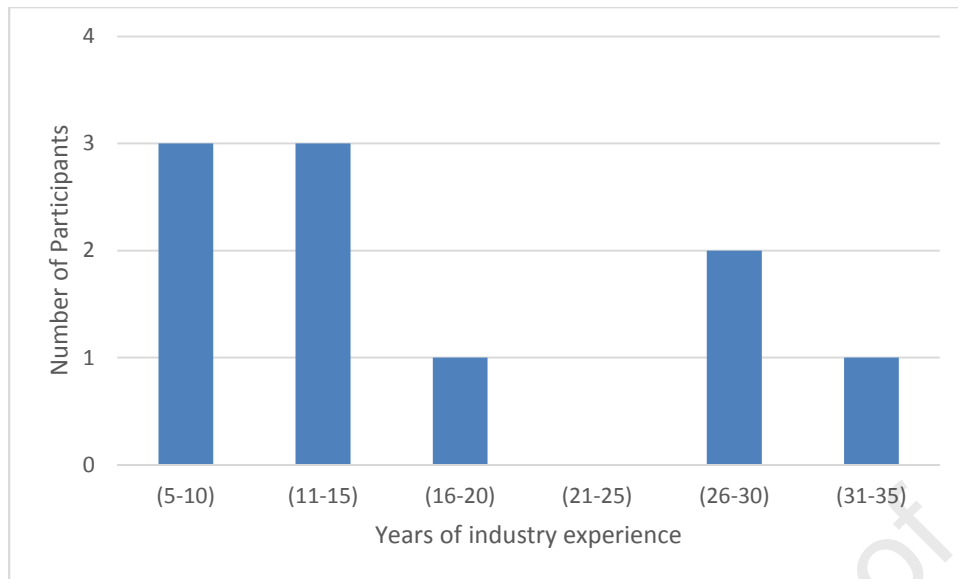


Figure 1 Distribution of the whole group's experience in academia or industry in years, collated into five-year 'bins' to protect their anonymity.

2.3. Consensus and stability

There is an ongoing discussion in the literature regarding what is considered consensus in a Delphi survey, and what descriptive or inferential statistics to use to measure and compare it [25–29,36]. In addition, some papers argue that, in fact, it is the stability of the responses over subsequent rounds, which should be the criteria for ceasing the survey [26]. In this study, we use both measures to analyse the results from the survey [26,27,35].

There is some broad agreement in the literature, that the use of interquartile range (IQR) and the median are the most robust descriptive statistics, as opposed to the mean and the standard deviation [26,29]. As a result, we used the IQR to measure the level of consensus (minimum value 1 for consensus), and the median to determine around which Likert response the consensus occurred. These criteria were determined by adapting other consensus criteria to a four-point Likert scale [29].

Studies with large Likert scales produce more precise results, thus have higher resolution than the four-point scale used here. Due to this low resolution, the IQR was often equal to 1, indicating the majority of answers were spread across two adjacent answers. The majority of the time, this occurred over both affirmative (agree-strongly agree) or negative (disagree-strongly disagree) responses, in which case we referred to it as 'broad consensus'. Where this occurred in the neutral space (disagree-agree), we did not consider this consensus, as the group is split in agreement.

Regarding stability, a less than 15% change in the answers between rounds was considered stable, as described by Scheibe et al., 1975 [37].

2.4. Delphi Round 1

Round 1 presented participants with a scenario regarding a future lunar outpost, included in Appendix A, based on 2020 NASA timelines [38] for a lunar surface asset, and extrapolated from it a future scenario in which the surface asset had grown (the scale of growth was left unspecified) between 2028 and 2040. Twenty-year timescales are typical in future-focused Delphi surveys [27]. Round 1 asked a series of seven open-ended questions that referenced the scenario, with commentary boxes intended to elucidate the important themes that informed their responses. These themes were then distilled in the analysis and formed the Round 2 & 3 questionnaires. The Round 1 questionnaire is available in Appendix B.

These themes were extracted from the open responses, where salient points were collated, and aggregated into categories that became the themes in Table 1. Themes J and K were broken down into subthemes to

account for the technologies discussed by participants within the broader themes of ISRU deployment and energy and power system technologies.

2.5. Delphi Round 2 & 3

The Round 1 themes were the basis for the Round 2 & 3 questionnaires, where participants were asked to score their agreement on a four-point Likert scale. We asked them to envision the outpost scenario and make their decision based on the balance of probabilities.

Since questions that are too tightly worded or restrictive in their phrasing lead to a narrow set of responses or abstentions, we chose to use high-level language in order to allow our participants the space to talk about the issues that they felt were important and elicit a broad range of responses, from which insights can be distilled, and a group discourse observed.

We also asked participants to rank five power generation technologies (see Table 5) by the amount of power provided by each technology at the outpost, in 2040. Participants were instructed to leave out any systems they did not think would be deployed. Participants were allowed to denote equal generation share using asterisks. Participants were also asked to rank eight inhibiting factors (see Table 6) in order of their importance.

In Round 3, the participants were presented with the same questions, alongside the distribution of answers from the group as a whole, and anonymised group commentary from the previous round. As we had defined the number of rounds, those Round 2 questions that were considered to have reached a general consensus were included in Round 3, as this study was interested in the stability of those answers when presented with the commentary and statistical feedback.

3. Results

3.1. Delphi Round 1

Below, the themes distilled from the open questions in Round 1 are presented. Where themes were clustered (e.g., energy and power system technologies) they are also numbered to differentiate them. These themes were used to develop the closed questionnaire of Rounds 2 and 3.

Table 1 Themes distilled from Round 1 questionnaire responses

A	The likelihood of crewed martian surface missions in 2040
B	US and global political instability
C	The uncertain impact of private space companies
D	The impact of COVID-19 (and subsequent pandemics) on space exploration timelines
E	Location siting uncertainty
F	Outpost occupancy uncertainty
G	Lander and vehicle ascent capacity
H	Outpost occupancy growth factors
I	Automation in 2040
J	ISRU deployment
J.1	Oxygen extraction scale (high)
J.2	Volatile extraction scale (med-high)
J.3	Mineral extraction scale (low – demonstration)
J.4	Regolith construction scale (low-med)
K	Energy and power system technologies
K.1	Fuel cells
K.2	Solar PV
K.3	Solar concentration

K.4	Nuclear reactor (night-time operation)
L	ISRU may require ~MW additional power
M	Non-ISRU activities in the 10s-100s KWe

3.2. Delphi Rounds 2 & 3

The results from Rounds 2 & 3 were extremely stable. In total in Round 3, there were only 7 changed responses from the previous round, and the impacts were well below the 15% threshold for stability. As a consequence, and for brevity, we therefore consider only the Round 3 data here.

Table 2 shows the statements that received strong, stable consensus from the group, typically in favour of 'Agree', but once in favour of 'Disagree'. The group felt that there would not be crewed surface missions to Mars by 2040, citing resource constraints of maintaining both a lunar outpost and efforts to land humans on Mars. It was noted in the commentary that crewed Martian orbit is more likely, based on current technological progress, while there was some mention of private space companies and the risks to any martian biome of contamination by humans. The participants also felt that human return to the lunar surface was likely to occur in the period 2026-2030, at least two years after the current NASA objective [38], and that regolith reduction was the most likely oxygen production technique, given uncertainties regarding water ice concentration.

Table 2 Question statements which reached stable, strong consensus from the group in Round 3. Bold items indicate around which Likert point consensus was reached.

No.	Statement	Strongly Disagree	Disagree	Agree	Strongly Agree	IQR	Median
1	Mineral extraction at the outpost will be at a demonstration and development phase in 2040	0%	0%	90%	10%	0	3
2	The first successful human return to the surface of the Moon will occur in the period 2026-2030	0%	10%	70%	20%	0.25	3
3	There will be crewed Martian surface missions by 2040	0%	80%	20%	0%	0.25	2
4	Any ISRU technology to be deployed at the outpost will be at TRL 5 during the detailed definition mission planning phase	10%	10%	70%	10%	0.25	3
5	There will be significant private space activities taking place on the Moon in 2040	0%	20%	60%	20%	0.5	3
6	A lack of sufficient certainty regarding water ice concentration will favour regolith reduction for oxygen production	0%	20%	60%	20%	0.5	3
7	Specific mass is the primary consideration for power system design	0%	22%	67%	11%	0.5	3

Table 3 shows those statements that received broad, stable consensus (e.g., there was stable agreement around two adjacent categories.). While these do not point to a specific level of agreement, as those in Table 2 do, they indicate whether the group were in agreement in the affirmative or negative Likert scale statements. Interestingly, these subjects tended to elicit more 'Strongly Agree' votes, splitting the affirmative votes across two categories and thereby increasing the IQR to unity. When the categories are aggregated into affirmative and negative, they show a similar consensus level to those in Table 2.

Table 3 Question statements which reached stable, broad consensus from the group in Round 3. Bold items indicate around which two Likert points the broad consensus was reached.

No.	Statement	Strongly Disagree	Disagree	Agree	Strongly Agree	IQR	Median
8	The development of nuclear thermal propulsion reactors will have no direct impact on any aspect of the lunar outpost project in 2040	0%	0%	60%	40%	1	3
9	Maximum lunar outpost crew occupancy is probably less than 20 persons in 2040	0%	10%	50%	40%	1	3
10	Outpost occupancy growth beyond 50 persons by 2040 is contingent upon commercial opportunities	0%	10%	50%	40%	1	3
11	Oxygen production at the outpost will be greater than 1000 kg per year in 2040	0%	0%	67%	33%	1	3
12	The majority of oxygen for fuel and life support could be extracted rather than launched	0%	10%	50%	40%	1	3
13	Useful levels of ISRU activities will add ~1 MW of power (electric or thermal) to outpost power consumption	0%	22%	56%	22%	1	3
14	Non-SRU activities will contribute less than 100 kW to power consumption	0%	33%	56%	11%	1	3

Table 4 shows those statements where the group was unable to reach a consensus as defined in this study. However, this table shows how the criteria we used is not perfect, Statements 17 & 18 have an IQR of 1.25, so have not reached consensus as we define it, but 80% of total votes cast in those statements were cast for an affirmative Likert option, and in many studies, 80% is considered strong consensus. Using our criteria, we cannot say that the group reached consensus on this; however, it indicates that large lunar outposts will not be the norm in 2040, but lunar habitation may be split across multiple terranes. In addition, it implies that the mission will likely be very similar to the ISS's current mission as an international low-gravity laboratory.

Interestingly, the vote was split almost entirely evenly across the neutral space in Statement 15, and it was the only statement to have a median exactly in the neutral area. This is reflective of differing levels of optimism surrounding the pandemic but makes clear that this is an area of uncertainty that some ISRU researchers and the space exploration community are concerned by. This uncertainty may have an influence on the timetable for returning to the lunar surface, which may compound the data from Statement 2, where the group noted that the first human return to the surface would take place at least two years after the NASA target of 2024.

Table 4 Question statements which remained in stable disagreement in Round 3

No.	Statement	Strongly Disagree	Disagree	Agree	Strongly Agree	IQR	Median
15	The COVID-19 outbreak will significantly alter lunar exploration timelines	0%	50%	40%	10%	1	2.5
16	A lack of sufficient certainty regarding water ice deposits at the poles will favour outpost siting on KREEP terrane	20%	40%	40%	0%	1.25	2
17	If there were 100 persons occupying the Moon in total by 2040, they would be spread over two or more outposts	0%	20%	40%	40%	1.25	3
18	The outpost's non-ISRU mission will be similar to the ISS and will act as an international laboratory in a low-gravity environment	0%	20%	50%	30%	1.25	3

19	Regolith construction will use thermal sintering approaches, not chemical binders	0%	44%	22%	33%	2	3
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3.2.1. Energy and power generation technology ranking

Table 5 shows the results from the ranking of power generation. The statement put to the participants was as follows: "Please rank the following power generation technologies by how much power they will provide at the outpost. Leave out any systems you don't think will be used. You may use an asterisk to denote a tie between two or more technologies (indicating an equal share of power production)."

Despite the caveat, only one participant made use of the opportunity to abstain (which accounts for the nine votes in solar concentration (electric), not ten), and none used an asterisk to denote a tie. The results were general agreement that solar photovoltaic would be the most widely used power generation technology, and that Solar concentration (electric) would be least used. For the middling three technologies, they were very closely ranked, suggesting that there is little agreement on how they would be deployed. This is most clear with Nuclear energy source, where it received two votes in each rank position, and there was a similar distribution with Solar concentration (thermal). Regenerative fuel cells, however, had a fairly strong consensus that it would be third, with 50% of the votes cast for that rank.

The final score was calculated using standard ranking methodologies, ascribing a value of 5 to Rank 1, and 4 to Rank 2, etc., tallying up the total scores and averaging over the number of responses. The highest-scoring technology was thereby ranked 1st.

Table 5 Power generation technology ranking. Solar photovoltaic was ranked first, with Solar concentration (electric) ranked last

Technology	Most power generated		Least power generated			Final score	Change from R2
	Rank: 1st	Rank: 2nd	Rank: 3rd	Rank: 4th	Rank: 5th		
Solar photovoltaic	6	2	1	0	1	4.32	0.397
Regenerative fuel cells	0	3	5	1	1	3.01	-0.014
Solar concentration (thermal)	2	2	1	3	2	2.92	-0.028
Nuclear energy source	2	2	2	2	2	2.91	-0.014
Solar concentration (electric)	0	1	1	4	3	1.83	-0.342

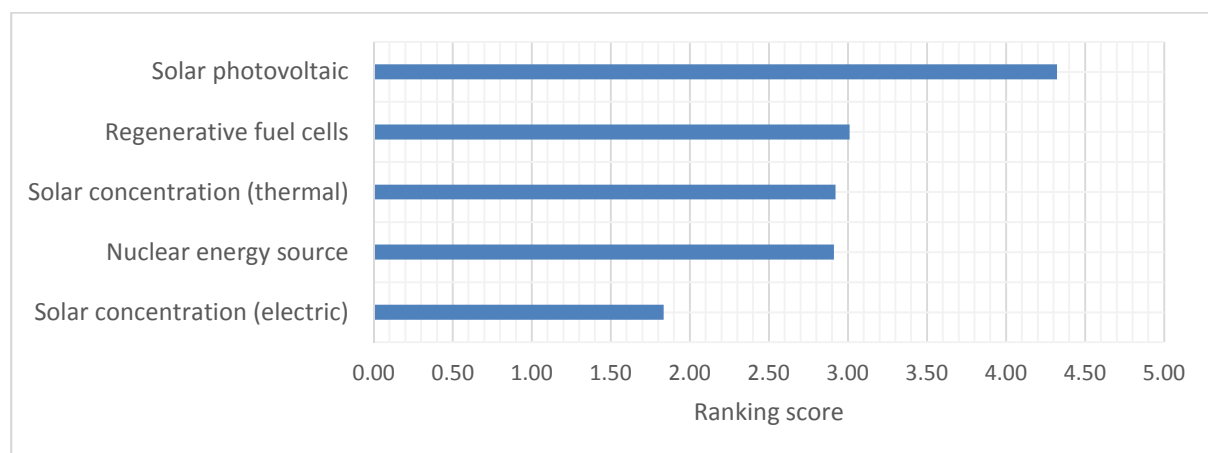


Figure 2 Power generation technology ranking. Solar photovoltaic was ranked first, with Solar concentration (electric) ranked last

3.2.2. Inhibiting factor ranking

The same methodology was applied to the inhibiting factors that were extracted from the themes in Round 1. Participants were asked to rank the inhibiting factors from most to least important. The results show a clearer gradient than was present in the Energy and power generation ranking, implying a greater group certainty regarding the level of importance ascribed to each inhibiting factor. Abstentions were treated as though the participant assigned zero importance to the inhibiting factor as per Section 3.2.1, however, of the two participants who abstained on this question, one was clear that they felt the question was phrased poorly and did not include other inhibiting factors such as radiation and dust mitigation. From this comment, it may have been the case that out phrasing of the question was misaligned with the participants' understanding of it. The inhibiting factors included within this question were distilled from the Round 1 themes where dust mitigation did not feature as an inhibiting factor.

Table 6 Inhibiting factor ranking. US and global instability was ranked first, with Insufficient automation ranked last

Technology	Most important								Least important	
	1st	2nd	3rd	4th	5th	6th	7th	8th	Final score	Change from R2
US and global political instability	9	1	0	0	0	0	0	0	7.90	0.3
Lander and ascent vehicle capacity	0	6	0	2	1	1	0	0	6.02	0.125
Energy generation and storage	0	3	4	2	1	0	0	0	5.94	0.45
In-situ development and demonstration of ISRU technologies	0	0	3	3	1	3	0	0	4.87	-0.2
Oxygen production capacity	0	0	0	2	4	1	0	1	3.28	-0.1
Coronavirus impact on space exploration activities	1	0	2	0	1	0	1	4	3.19	0
Location of outpost	0	0	1	0	0	2	4	1	2.48	-0.125
Insufficient automation	0	0	0	1	1	1	3	2	2.32	-0.45

US and global political instability is ranked as a clear first and the most important inhibiting factor in the development of a lunar outpost. One participant noted that the pandemic and its impacts are inseparable from political instability as the economic cost of recovery will eat into the discretionary spending available to space agencies across the globe, and was surprised at its low rank (6th). It seems from Table 6 and Figure 3 that three major inhibiting factors were ascribed a high value by participants; US and global instability, Lander and ascent vehicle capacity, and Energy generation and storage. In-situ development and demonstration of ISRU technologies were generally considered of middling importance, with no votes in the top or bottom two ranks.

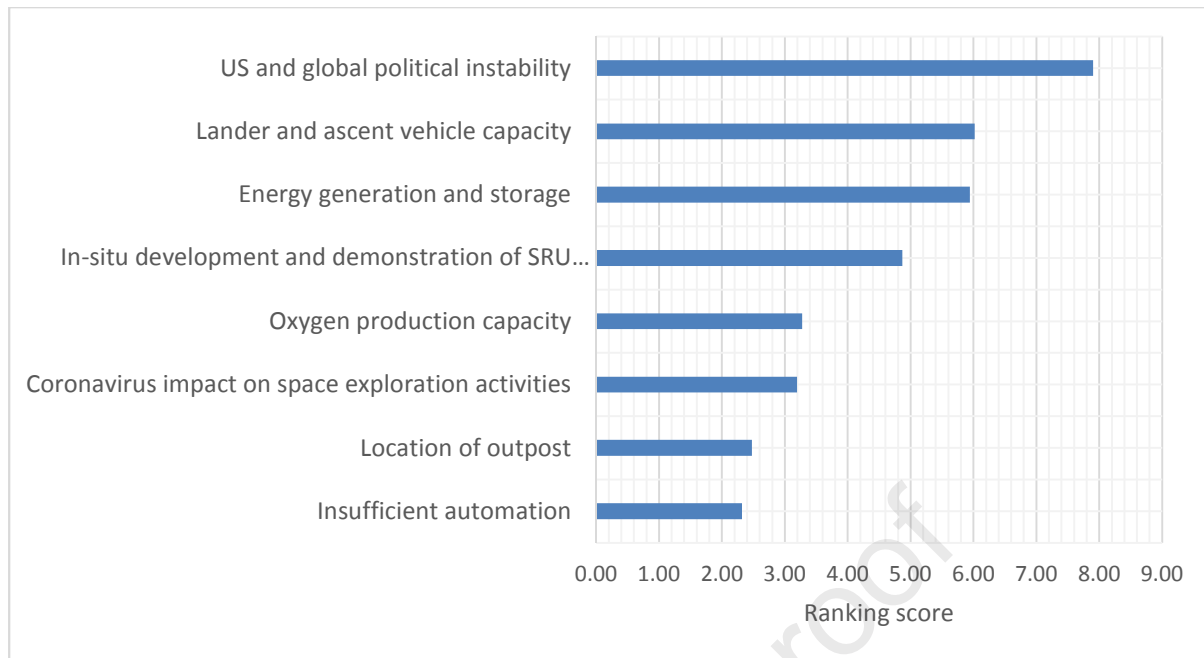


Figure 3 Inhibiting factor ranking. US and global instability was ranked first, with Insufficient automation ranked last

4. Discussion

4.1. Timeframes

The participants were very confident in Statement 2, that the next human return to the surface of the Moon would occur in the time period 2026-2030, which is at least two years after the NASA official timeline. This mismatch in expectations implies that the participants are less confident about meeting that deadline. Commentary for this statement was sparse, but one participant noted that the political process in the US, as well as Covid-19 might impact upon these timelines, while another stated that 2026-2030 appeared to be a promising timeframe for a human return to the Moon, from a political perspective. The implication of this commentary is that the participants were primarily concerned by political uncertainty, and not by technological challenges.

4.2. Methods

Consensus measures vary significantly between studies, and some have suggested that they are developed retrospectively. This study adopted techniques from a number of other studies to suit the questionnaire design (e.g., four-point Likert-scale), which included a forced-choice scale to limit neutral responses. This methodology allowed for two types of consensus; where an IQR of less than 1 occurred (strong consensus), and where an IQR equal to 1 occurred (broad consensus). The majority of cases of broad consensus had distributions across either both the affirmative (Agree, Strongly agree) or both the negative (Disagree, Strongly disagree), but in Statement 15, this occurred between Agree and Disagree (a median of 2.5). So, although the criteria is met for broad consensus, the group is evenly split in agreement. Any future study would need to address how neutral consensus is accounted for in forced-choice Likert studies.

4.3. ISRU

The group were in agreement (78% affirmative votes, 22% negative votes) that useful levels of in-situ resource utilisation would add around 1 MW of power (electrical or thermal) to the outpost power requirements, as shown in Statement 2. This implies that a sustainable base constructed with ISRU techniques and producing some fraction of its own consumables would require a space power system in excess of any that has so far

been developed or proposed. Some participants noted that the power system needs were very uncertain and that since there had been very little iteration done on ISRU technologies, efficiency may improve. However, we suppose most ISRU processes require raising the temperature of regolith. In that case, they will be bound by the specific heat capacity which will govern the thermodynamic lower-bound for energy, and this will require significant infrastructure even where it is done by solar concentration [1]. This is especially important in construction that uses bulk regolith for fabricating roads, landing pads and shelters, due to the high volume of regolith processed for such structures.

On the subject of whether these processes would be done by a chemical binder or some sintering approach, the group was split; Strongly disagree 0%, Disagree 44%, Agree 22%, Strongly agree 33%. The commentary on this point was equally split, with some participants making clear that they felt the additional launch mass of binders was prohibitive, while some noted that the speed at which it could be developed and deployed, and the reduced energy requirements made it more likely that a US-led outpost would use it. Some noted that there would likely be a mix; bulk processing of regolith (roads, landing pads, shelters, etc.) would be done through sintering, while finer work could be accomplished through binder-based technologies. Given the significant infrastructure and R&D investment required for thermal sintering (e.g., large electrical power system, solar concentrators, brick fabricators etc.), and the possibility of long lead-times for technology development, policy decisions regarding the choice of approach should be made in the near-term. This would reduce the technological uncertainty and allow researchers to concentrate their efforts on the relevant technical challenges.

4.4. Ranking exercises

The group were extremely clear in their assertion that the most important inhibiting factor facing the development of a sustainable lunar outpost by 2040 is US and global instability. The commentary that touched on the subject ranged from the economic impact of coronavirus in the US (and the rest of the world), which will have an effect on discretionary funding in the coming years, to changes in policy as a result of new governments and administrations and their new priorities. While projects that have a significant defence or economic value are unlikely to be cancelled, the development of a lunar outpost has fewer tangibles, making it vulnerable to changes in policy. Researchers and organisations involved in developing such a project need to ensure that they have a robust case for carrying out the activity in order to protect their funding in times of economic stress.

The next most important inhibiting factors are 'Lander and ascent vehicle capacity' and 'Energy generation and storage', which are tied in second place with importance ranking scores of 6.04 and 5.96 respectively. Regarding the lander and ascent vehicle capacity, one participant noted that this would ultimately determine the outpost occupancy and technology inventory. For example, the power system for sintering regolith into radiation protection covers would be in the MW-scale (thermal or electrical power), and these power systems might be in the region of tens of tonnes [1]. From the NASA Human Landing System (HLS) Requirements (Attachment F) document [39], the Artemis HLS of the 2020s will be sized for approximately 1 tonne of payload from lunar orbit to the surface, which is considerably less than would be necessary in 2040. As a result, the lander and ascent vehicle needs to see significant evolution before this bottleneck is overcome.

Equally important to the participants, and, as shown above, linked to the lander vehicle, is the energy generation technology. As detailed above, participants expected an additional MW of power required for ISRU at the outpost in 2040, and possibly more. This is significantly more power than is currently available in space and could be achieved through the use of thermal power production from sunlight where the ISRU process relies on heat only, solar photovoltaic or a nuclear power source. The group felt in the energy technology ranking exercise that solar PV would be the primary energy technology deployed, but a 1MW solar PV system could be in excess of 20 tonnes [1]. A nuclear power system could provide 1 MW without the need for a PV field of several thousand square metres (albeit with significantly more mass), but many participants noted the political distaste for the deployment of nuclear power systems in space. However, in contrast to these comments from the group, the US Department of Energy (DoE) has released a Request for Information (RFI) regarding 10 kW fission surface power reactors [40]. The requirements also stipulate a 1 km cable and a mass of 2000-3500 kg. The lower weight band is defined as a stretch goal to allow the reactor mass to dovetail with

the HLS. The requirements also note that the reactor should be ready for launch by no later than December 31st, 2026.

Despite this RFI from the DoE, 10 kW remains a drop in the ocean compared to the MW the group thought would be needed for construction and other ISRU projects. Even used in a modular fashion, it would take 100 such reactors to reach that power output. This seems to suggest that the US is pursuing a low-power, higher launch mass approach, at least in the early stages of lunar habitation.

The outpost location was considered to be broadly unimportant, and the group felt in the commentary that there were significant challenges in accessing water ice resources in permanently shadowed regions (PSRs). However, some specific polar locations have access to longer periods of sunlight which provide missions with more energy system flexibility. The commentary from participants implied that the siting was important, but that there was uncertainty regarding water ice deposits and their accessibility in PSRs.

5. Conclusions

We recruited a group of subject matter experts of considerable experience in both industry and academia, who provided us with valuable insights into the technological and policy challenges facing a lunar outpost in 2040. The responses will prove useful to policymakers and provides a basis to begin the process of prioritising technology development for ISRU processes.

Some of the statements drew considerable discussion and divergence between participants, from which the majority of the conclusions were drawn – uncovering the uncertainties and divergence of thought within the group was a key principle of the study.

All answers to the survey were extremely stable with negligible differences between rounds. The majority of the statements received some level of agreement (broad or strong consensus), apart from Statements 15-19 in Table 4.

From the group responses, we have identified three major technical challenges for the development of a lunar outpost in 2040; developing high power energy infrastructure, lander and vehicle ascent capacity, and mission architectures and technical approaches.

The group agreed that In-Situ Resource Utilisation (ISRU) could require an additional 1 MW of power (thermal or electric) due to the high-energy nature of many ISRU processes, and the diffuse nature of the ISRU products themselves. Given the significant infrastructure investment and lead-times needed to develop such power systems, policymakers need to make decisions in the near-term about their approach to ISRU construction for any lunar outpost. Decisions made ahead of time will allow space agency researchers and academics to concentrate their efforts on the relevant technical challenges in delivering construction technologies.

The lander and ascent vehicle capacity was highlighted as a bottleneck in mission design, and recent RFIs from NASA have called for approximately 1 tonne of payload from lunar orbit to the surface, which is considerably less than would be necessary in 2040. Given the other elements in NASA's Artemis mission post-2024, such as the habitable mobility platform, it is likely that the lander and ascent vehicle will be iterated and upgraded for larger payloads in the years following 2026. However, mission planners need to account for possible large payloads in the coming decades.

Mission architectures and technical approaches will also deeply influence the technological development of ISRU platforms. This is most stark in the choice of regolith construction approach for landing pads, roads, and radiation and micrometeorite protection. It can be summarised as a choice between high-power and low launch mass, and low-power and high launch mass architectures. Both approaches will require significant lead times and technological development which are not easy to compress. Therefore, these decisions need far more attention from space agencies and academia for technological feasibility and economic studies.

From the group responses, we have also identified three major policy challenges for the development of a lunar outpost in 2040; US and global political instability, extended timeframe for the first lunar landing, and political distaste for nuclear energy in space.

Participants thought that the first human return to the lunar surface would occur at least two years after NASA timelines, in the period of 2026-2030, rather than 2024. The commentary implied that this lack of confidence was a result of the uncertainty in US policy in the coming years.

The group was uncertain about the precise energy mix at the outpost, but there was general agreement that solar PV would be a significant contributor, while nuclear power sources were very uncertain, gaining two votes in each ranking position. The choice of energy source is clearly still contentious, with the group noting that there was political distaste for nuclear power in space among policymakers. This is contrasted, however, with the US government's recent RFI regarding multi-kilowatt reactors for space. This RFI implies that the US is pursuing a diverse mix of energy technologies, including solar PV and energy storage, as well as nuclear fission.

There was robust disagreement regarding the impacts of Covid-19 on space exploration timelines, with the group split nearly 50:50 between affirmative and negative, which remained stable between rounds. In the ranking questions, fewer abstentions and ties were recorded than expected, possibly a result of participants using the lowest ranks to indicate their belief that particular technology would not be present. In future, a more effective methodology may be to ask participants to pick a certain number of ranking items, such as three power generation technologies from five, effectively a forced choice system.

Outpost location was not considered to be an important inhibiting factor; neither was progress toward automation.

6. Acknowledgements

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Appendix A – Round 1 Scenario and Instructions

The following scenario was circulated to participants on receipt of their signed consent forms.

Scenario

In this questionnaire, we ask you to consider a scenario in which there is lunar surface outpost operating in 2040. It is a US-led, international effort similar to the International Space Station. Back-casting from 2040 we should assume that 2024 saw the first human mission to the Moon since Apollo, and in 2028 the 'Lunar Surface Asset'¹ was deployed to complement the Lunar Gateway. The Gateway has grown in the years leading up to 2040 in-line with current (2020) concept plans. Between 2030 and 2040 there have been crewed missions to Mars, using technology developed at, or tested via, the lunar outpost.

Support in the US, and internationally, for a lunar outpost remains strong in the 2030s as it delivers key technology, training, and resourcing opportunities for the more remote and challenging Mars outpost which still lies ahead. Lunar space resource utilization (SRU) and its underpinning technologies are of special interest to the US and international partners involved in both the Moon and Mars missions. SRU provides manifest opportunities for cost reduction and self-reliance going forward.

Instructions

Keeping in mind your expectations for a crewed lunar outpost in 2040, please answer the questions on the following page. Please note that any technology you imagine deployed on the Moon in 2040 will need to have achieved a relatively high technology readiness level (e.g. TRL 7) by 2030 if it is to be in situ by 2040.

Each answer has a comments / rationale section where you can elaborate on your response. Please detail your rationale for your answer here and include any commentary on the question structure.

Questions 1-3 should take no more than 10 minutes total to complete, and Questions 4-7 may take up to 30 minutes to complete.

If there is a question you feel you cannot answer, please note this and your rationale for opting out in the comments section. This will not affect your participation in the study's second or third rounds.

If these instructions are not clear, please contact the corresponding researcher, Chris Spedding, at christopher.spedding@open.ac.uk.

Thank you for taking part, the questions begin on the next page.

¹ https://www.nasa.gov/sites/default/files/atoms/files/america_to_the_moon_2024_09-16-2019.pdf (Slide 17)

Appendix B – Round 1 Questionnaire

Does the scenario outlined above seem likely?

Likely or not	Comments / rationale
Yes / No	

Is the lunar outpost based at the poles or elsewhere?

Location	Comments / rationale

What will the maximum occupancy of the outpost be?

Crew complement	Comments / rationale

What SRU technologies (hydrogen / oxygen extraction, construction etc.) will be deployed at the outpost? In the left-hand column, please list the technologies you expect to see deployed.

ISRU technologies	Comments / rationale Please be sure to comment on enabling and inhibiting factors

What is the scale of the specific SRU technologies you noted in your answer to Q4? If you have specific figures in mind, please include them.

Scale (low/med/high)	Comments / rationale Please be sure to comment on enabling and inhibiting factors
	Low: Some small-scale deployment for testing Medium: Technology deployed as an active resource management element of the outpost High: Technology contributes significantly to resource management of the outpost

What will the power source for this outpost be? If it is a combination, please state roughly the technology ratios.

Power source	Comments / rationale Please be sure to comment on wider contextual or scenario considerations

Given your thoughts on the types and scale of ISRU technologies, what are the likely average peak and minimum electrical loads needed for the outpost? If possible, please answer with an approximate value in kW.

Electrical load	Comments / rationale Please comment on any contingent assumptions
Peak: Average: Minimum:	

Questionnaire ends

Thank you for participating. Please email the completed form to the corresponding researcher, Chris Spedding, at christopher.spedding@open.ac.uk. We will then collate the responses and develop the Round 2 questionnaire.

Appendix A – Round 1 Scenario and Instructions

Scenario

In this questionnaire, we ask you to consider a scenario in which there is lunar surface outpost operating in 2040. It is a US-led, international effort similar to the International Space Station. Back-casting from 2040 we should assume that 2024 saw the first human mission to the Moon since Apollo, and in 2028 the 'Lunar Surface Asset'¹ was deployed to complement the Lunar Gateway. The Gateway has grown in the years leading up to 2040 in-line with current (2020) concept plans. Between 2030 and 2040 there have been crewed missions to Mars, using technology developed at, or tested via, the lunar outpost.

Support in the US, and internationally, for a lunar outpost remains strong in the 2030s as it delivers key technology, training, and resourcing opportunities for the more remote and challenging Mars outpost which still lies ahead. Lunar space resource utilization (SRU) and its underpinning technologies are of special interest to the US and international partners involved in both the Moon and Mars missions. SRU provides manifest opportunities for cost reduction and self-reliance going forward.

Instructions

Keeping in mind your expectations for a crewed lunar outpost in 2040, please answer the questions on the following page. Please note that any technology you imagine deployed on the Moon in 2040 will need to have achieved a relatively high technology readiness level (e.g. TRL 7) by 2030 if it is to be in situ by 2040.

Each answer has a comments / rationale section where you can elaborate on your response. Please detail your rationale for your answer here and include any commentary on the question structure.

Questions 1-3 should take no more than 10 minutes total to complete, and Questions 4-7 may take up to 30 minutes to complete.

If there is a question you feel you cannot answer, please note this and your rationale for opting out in the comments section. This will not affect your participation in the study's second or third rounds.

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Thank you for taking part, the questions begin on the next page.

¹ https://www.nasa.gov/sites/default/files/atoms/files/america_to_the_moon_2024_09-16-2019.pdf (Slide 17)

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Appendix B – Round 1 Questionnaire

Does the scenario outlined above seem likely?

Likely or not	Comments / rationale
Yes / No	

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Location	Comments / rationale

What will the maximum occupancy of the outpost be?

Crew complement	Comments / rationale

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ISRU technologies	Comments / rationale Please be sure to comment on enabling and inhibiting factors

What is the scale of the specific SRU technologies you noted in your answer to Q4? If you have specific figures in mind, please include them.

Scale (low/med/high)	Comments / rationale Please be sure to comment on enabling and inhibiting factors
	Low: Some small-scale deployment for testing Medium: Technology deployed as an active resource management element of the outpost High: Technology contributes significantly to resource management of the outpost

What will the power source for this outpost be? If it is a combination, please state roughly the technology ratios.

Power source	Comments / rationale Please be sure to comment on wider contextual or scenario considerations

Given your thoughts on the types and scale of ISRU technologies, what are the likely average peak and minimum electrical loads needed for the outpost? If possible, please answer with an approximate value in kW.

Electrical load	Comments / rationale Please comment on any contingent assumptions
Peak: Average: Minimum:	

Questionnaire ends

Thank you for participating. Please email the completed form to the corresponding researcher, Chris Spedding, at christopher.spedding@open.ac.uk. We will then collate the responses and develop the Round 2 questionnaire.

Highlights:

- US and global instability, power for ISRU and lunar lander capacity are critical barriers to a lunar outpost
- ISRU processes could add 1 MW of power requirements to lunar outpost
- ISRU researchers lack confidence NASA lunar exploration timelines
- Group could not reach consensus on Covid-19's impact on space exploration

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: